JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
VOL. 35, NO. 6 AMERICAN WATER RESOURCES ASSOCIATION DECEMBER 1999

HOW CLIMATE UNCERTAINTY SHOULD BE INCLUDED IN GREAT LAKES MANAGEMENT: MODELING WORKSHOP RESULTS[1]

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ABSTRACT: In two workshops, we evaluated decision analysis methods for comparing Lake Erie levels management alternatives under climate change uncertainty. In particular, we wanted to see how acceptable and effective those methods could be in a public planning setting. The methods evaluated included simulation modeling, scenario analysis, decision trees and structured group discussions. We evaluated the methods by interviewing the workshop participants before and after the workshops. The participants, who were experienced Great Lakes water resources managers, concluded that simulation modeling is user-friendly enough to enable scenario analysis even in workshop settings for large public planning studies. They felt that simulation modeling can improve not only understanding of the system, but also of the options for managing it. Scenario analysis revealed that the decision for the case study, Lake Erie water level regulation, could be altered by the likelihood of climate change. The participants also recommended that structured group discussions be used in public planning settings to elicit ideas and opinions. On the other hand, the participants were less optimistic about decision trees because they felt that the public might view subjective probabilities as difficult to understand and subject to manipulation.

(KEY TERMS: water resources planning; climate change; decision support systems; risk analysis; Lake Erie; Great Lakes.)

INTRODUCTION

Two workshops on Climate Change and Great Lakes Management were held in 1995 at Case Western Reserve University in Cleveland, Ohio to evaluate methods for including climate change and other risks in Great Lakes planning. The 15 participants were experienced Great Lakes water resource managers. They represented government agencies and private organizations [U.S. Army Corps of Engineers, USEPA, Great Lakes Environmental Research Laboratory (GLERL), Environment Canada, Case Western Reserve University, University of Toronto, Waterfront Regeneration Trust (Toronto), World Bank, and the International Joint Commission (IJC)]. Most had participated in the IJC Levels Reference Study (1993).

The Levels Reference Study resulted from the need to better manage Great Lakes water resources for water level extremes, especially after high levels in the late 1980s caused extensive shoreline damage. A broad range of shoreline and water level management options was evaluated in a multiple criteria decision framework. The criteria were defined as the range of water resource uses that are influenced by water level variability, including hydropower, navigation, wetlands, and shoreline damages. Although climate warming may decrease mean water levels in the Lakes (Croley, 1990), the IJC study did not evaluate the robustness of the alternatives under climate change scenarios due to time and cost constraints.

The workshops sought to analyze how climate change and its impacts can be more fully incorporated into a public planning study. Specifically, the workshops addressed the following questions:

- Can a decision support system (DSS) be useful for providing climate change information for management of the levels of the Great Lakes?
- Given climatic uncertainties, how can robustness of management strategies and worth of information be assessed?
- Can assumptions about climate change affect levels management decisions?

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[1] Paper No. 98041 of the *Journal of the American Water Resources Association.* **Discussions are open until August 1, 2000.**

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The first workshop emphasized scenario analysis – the evaluation of lake levels management alternatives under certainty (either present climate or a climate change scenario based on global circulation models (GCMs) run under a doubled concentration of greenhouse gases, denoted $1xCO_2$ and $2xCO_2$, respectively). In the second workshop, participants used decision trees to explore climate uncertainties. Structured group discussions supplemented the DSS-based exercises. To assess the effectiveness of the DSS and the workshop in general, the participants were asked to fill out questionnaires before and after both workshops.

The DSS consists of a simulation model and decision analysis tools. The simulation model links climate change scenarios to Great Lakes hydrology and then, in turn, to economic and environmental impact indices. The decision analysis tools include a multicriteria decision making (MCDM) framework and decision trees (Chankong and Haimes, 1983; Keeney and Raiffa, 1993; Hobbs *et al.*, 1992; Clemen, 1997). The DSS was designed to be user-friendly to facilitate scenario analysis. The DSS allowed the users to easily enter, check, and modify input data, and visualize and communicate results. Such systems can also assist negotiations by clarifying the implications of alternative assumptions and value judgments (Thiessen and Loucks, 1992; Hamalainen *et al.*, 1999).

The purpose of this paper is to summarize the answers to the above questions that the workshop participants provided. The paper's outline is as follows. We first provide background on possible impacts of climate change upon Lake Erie, management alternatives, how climate change might affect those alternatives, and methods for evaluating the alternatives under uncertainty. We then describe the DSS. A summary of the workshop exercises and conclusions conclude the paper; details are available in Chao *et al.* (1997).

BACKGROUND

The prospect of possible climate change is important for some, but not all, water resource investment decisions (Hobbs *et al.*, 1997). Characteristics that increase the relevance of climate include: long-term commitments that are irreversible or costly to alter (e.g., engineering projects, such as dams, and also treaties, such as the Niagara River Treaty); benefit or cost streams that could be affected by climate change uncertainty; large one-of-a-kind projects (as opposed to increments of capacity); and resource commitments that can be delayed until more information is obtained. Control structures for regulation of the levels of Lake Erie would meet such criteria.

The primary water level management options considered in the Levels Reference Study were modified 2-lake regulation and 3-lake regulation. Two-lake regulation represents the present system of regulating Lakes Superior and Ontario, which have control structures at their outlets (Figure 1). The IJC has recognized the need to alter the operating rules ("modified 2-lake regulation") due to changes in priorities, particularly environmental impacts along the St. Lawrence River Seaway and recreational boating (IJC 1993). Three-lake regulation would add Lake Erie regulation to the present 2-lake system by building a control structure at the lake outlet at Buffalo, New York.

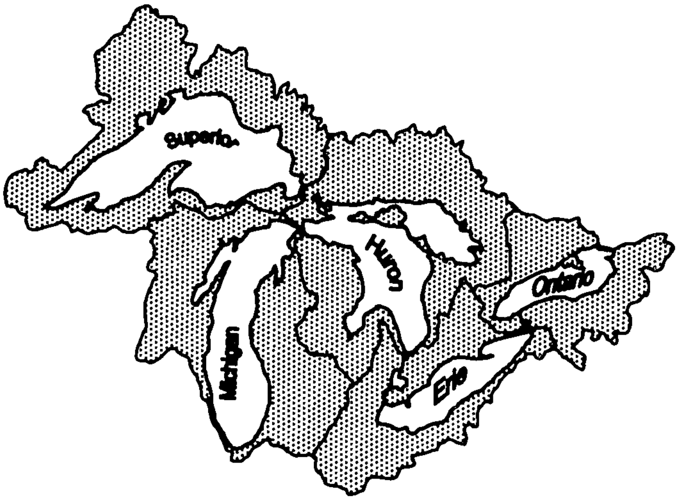


Figure 1. Map of the Great Lakes.

The Levels Reference Study recommended modified 2-lake regulation over 3-lake regulation as the preferred water level regulation measure. The capital cost and the environmental damages downstream of the Lake Erie control structure were seen as the primary drawbacks of 3-lake regulation. Furthermore, under 3-lake regulation, the benefit from reduced shoreline property damage would be far less than the disbenefits to hydropower and navigation interests.

But how would these alternatives perform if the climate becomes warmer? Integrated studies, which link climate change scenarios to water quality and quantity scenarios and then to socioeconomic and environmental impacts, have been conducted to evaluate the sensitivity of the present 2-lake regulation to climate change (Smith and Tirpak, 1989; Hartmann, 1990; Koshida *et al.*, 1993).

As an example of the sensitivity results from an integrated model, Table 1 lists the categories of climate change impacts upon Lake Erie that are modeled in the DSS of this paper. The modeled impacts are defined in the next section. Values shown are averages, as estimated by our DSS, that result from both the present 2-lake regulation system and for a 3-lake regulation proposal. The $2xCO_2$ scenario is a steady-state climate change scenario from the Canadian Climate Centre Global Circulation Model (CCC-GCM) (McFarlane *et al.*, 1991). The results show that a 1.5-meter drop in mean Lake Erie water levels under 2-lake regulation can lead to significant impacts, both negative and positive. The two largest sectors in monetary terms, hydropower and navigation, have large negative impacts. Flooding and erosion damage, a politically significant sector, is reduced significantly under this climate change scenario. The table also shows that if Lake Erie were controlled, impacts to navigation and cold water habitat would be lessened. However, Croley (1993) found that water levels might drop anywhere between 0.5 to 2.5 m, which means the magnitude of these impacts is highly uncertain. Because of this uncertainty and the complexity of the system, we attempted to make the DSS as user-friendly as possible to allow the users to conveniently explore different model assumptions.

Although the IJC found 2-lake regulation better than 3-lake regulation under the present climate, it is possible that 3-lake regulation could be better under climate warming. Scenario analysis, which was used in the first workshop, is one approach to evaluating alternatives and their performance under climate change. For instance, scenario analysis might compare 2-lake and 3-lake regulation under $1xCO_2$ and $2xCO_2$ scenarios (Table 1). If it is shown that one regulation scheme is better than the other under all reasonable climate scenarios, then there is no need to analyze further, as the hypothesized climate change would not affect the decisions.

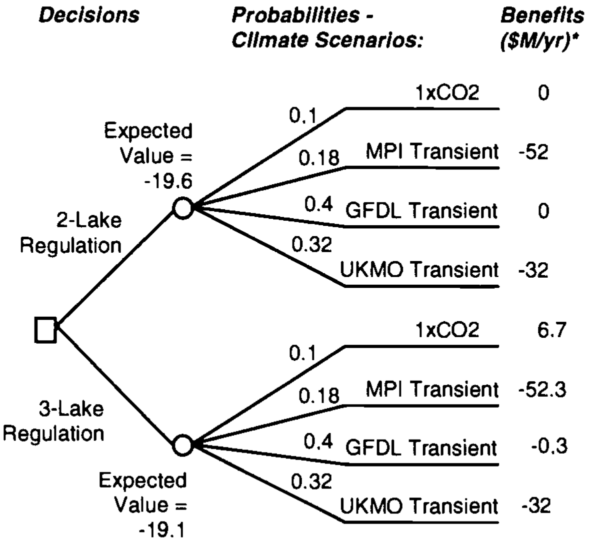
If, however, the rank order of options depends upon the scenario, then one ought to consider the likelihood of climate change. Decision trees, which were used in the second workshop, calculate the net expected benefits of decisions by incorporating subjective probabilities of the climate scenarios. Figure 2 shows an example decision tree for the 2- vs. 3-lake regulation decision. It is comprised of nodes for decisions (squares) and chance (circles), while the payoff for each alternative and scenario is shown at the end of a branch. The two branches of the decision node represent 2-lake and 3-lake regulation alternatives, respectively. A chance node represents the uncertain future that affects the stream of benefits and costs for that decision. Each of its branches represents some future climate scenario. In this simple tree, there are four scenarios: no change and three transient warming scenarios based on three different GCMs. These GCMs include models developed by the Max Planck Institute (MPI), United Kingdom Meteorological Office (UKMO) and Goddard Fluid Dynamic Laboratory (GFDL) (Cubasch *et al.*, 1992; Murphy, 1994; Manabe *et al.*, 1991). (In contrast to steady state climate change scenario which assumes that the climate has reached equilibrium under $2xCO_2$ conditions, the transient scenarios assume that the climate changes slowly from the present conditions to $2xCO_2$ conditions over a period of time.)

The user's degree of belief in the various scenarios is represented in the decision tree by subjective probabilities attached to the scenario branches. The probabilities shown in Figure 2, along with the net annualized benefits, are based on assessments by one subgroup. Expected net benefits for each option are calculated by assigning probabilities to each branch and summing the probability-weighted payoff values. The optimal decision is that which maximizes net expected benefits (or expected utility, if a nonlinear utility function is used to represent risk preferences; Clemen 1997). In this case, 3-lake regulation has a

TABLE 1. Average Lake Erie Water Resources Impacts Under 2-Lake and 3-Lake Regulation for $1xCO_2$ and $2xCO_2$ Steady State Scenarios.

Management Plan and Scenario	Erie Levels (m)	Hydropower Value ($M/yr)	Flooding and Erosion Damage ($M/yr)	Navigation Cost ($/ton)	Erie Wetland Elevation Range (m)	Cold Water Fish Habitat (km^3)
2-Lake, $1xCO_2$	174.1	936.3	23.8	3.70	0.18	13.4
2-Lake, $2xCO_2$	172.6	791.0	3.8	5.03	0.32	1.9
3-Lake, $1xCO_2$	174.0	932.5	17.7	3.69	0.02	10.9
3-Lake, $2xCO_2$	173.4	798.0	6.8	4.58	0.24	3.3

marginally higher net benefit, primarily because of its better performance under the existing climate. The two policies are nearly indistinguishable if the climate warms and lake levels drop. It should be noted that Figure 2 is just an example of the results. Each subgroup's results were different, depending on their criteria weights, the size of the control structure, assumed shoreline management measures, interest rate, and probabilities.



*Annualized net benefits measured relative to the base case of 2-lake regulation under $1xCO_2$.

Figure 2. Decision Tree for 3-Lake Regulation Under Climate Change Uncertainty.

Since the probability of climate change is disputed, the net expected benefits must be calculated from the decision maker's subjective belief. If one absolutely believes that climate warming that significantly affects lake levels will occur, then the no warming scenario should be assigned a zero probability, denoted $P(1xCO_2) = 0$. On the other hand, if one believes such warming will not happen, then $P(1xCO_2) = 1$. Even if managers are unsure or disagree about these probabilities, a sensitivity test on the decision tree can be done to calculate the probabilities at which the optimal decision changes from 2-lake to 3-lake regulation.

THE DECISION SUPPORT SYSTEM

Figure 3 shows the components of the DSS. Consistent with the principles of good DSS design, potential users in the Corps of Engineers were consulted concerning the questions it would address and its structure, and modifications were made in response to feedback from workshop participants. Most of the models were originally developed by IJC and Great Lakes Environmental Research Laboratory (GLERL) or were meta-models based on their results. Meta-models are simplified models in which unneeded detail is abstracted by approximating outcomes of a complex process model through statistically validated parametric forms (Bouzaher *et al.*, 1993). The variables across the bottom of the figure are the inputs (decisions or scenarios) that the user must select. The time-step of the model is one month. A simulation length of 60 years was chosen to capture the effects of transient climate change scenarios. The DSS was implemented in STELLA, a user-friendly, graphical, system simulation program based on Forrester's systems dynamics methodology (High Performance Systems, 1994). Previously, STELLA has successfully served as the basis of public participation processes in drought planning for the Corps of Engineers (Palmer *et al.*, 1993). The output from the STELLA

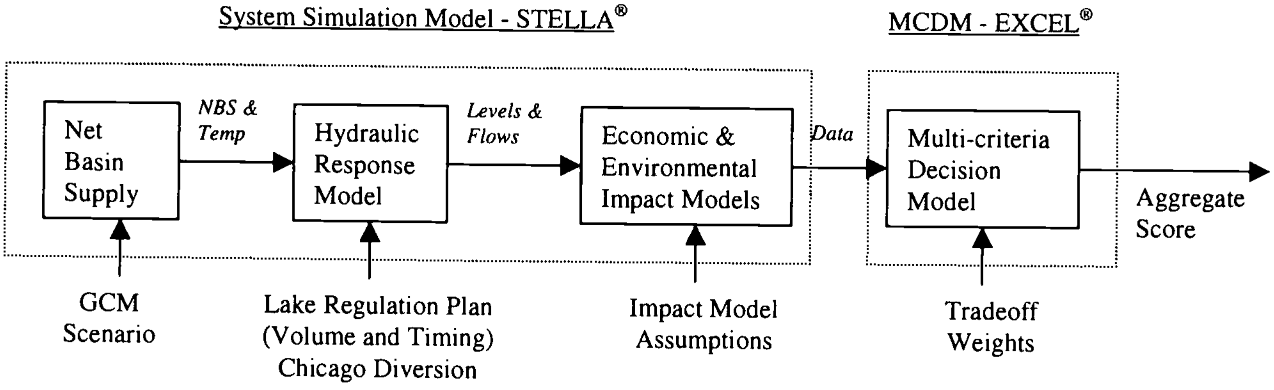


Figure 3. Decision Support System Structure.

model is fed to an EXCEL® spreadsheet that includes a multi-criteria decision-making interface and a decision tree, described below.

Net Basin Supply Model

The hydrological/hydraulic portion of the simulation model is a mass balance of inflows and outflows to the lakes. The net inflow into a lake, less channel flows between lakes, is called the Net Basin Supply (NBS), which is defined as the sum of runoff and direct-lake precipitation minus lake evaporation. Rather than explicitly model runoff and lake evaporation processes under alternative climates, we developed a meta-model based on process models developed by GLERL to obtain climate change scenarios of NBS. The meta-model perturbs historical time series of NBS to simulate transient climate change scenarios.

The model first calculates the percentage change in mean NBS for each lake under steady-state $2xCO_2$ scenarios as a function of the user's hypothesized change in mean temperature and precipitation; the function is a regression model based on simulations by Croley (1990) (Venkatesh and Hobbs, 1999). It is assumed that this level of impact will be reached in six decades. Then a time series of NBS, based on historical data, is shifted, where the perturbation increases proportionally over six decades to the $2xCO_2$ percentage change. This method is simplistic; but given the great uncertainties surrounding regional climate change, it is of paramount importance to provide users a convenient means of looking at a range of NBS scenarios that are broadly consistent with alternative climate assumptions and the Croley (1990) runoff simulation model.

Hydraulic Response Model

The hydraulic response model, which is a reservoir routing model, calculates the channel flows from lake-to-lake (Quinn, 1978; Hartmann, 1987). There are five reservoirs, one for each lake: Superior, Michigan-Huron, St. Clair, Erie, and Ontario. The mass balance accounts for NBS, man-made diversions, and channel flows (open and regulated). The diversions are Chicago River, Welland Canal, and the Long Lac and Ogoki River Diversion. The Ontario rules are an approximation to the real rules because Ottawa River flows are not modeled by the system and its time-step is monthly rather than the rules' quarter-monthly step. The Lake Superior rules are based directly on those in Leonard and Todd (1982). Since the model must support scenarios of NBS under climate change, both sets of rules were modified so that they would not fail during extreme flows (Lee and Quinn, 1992).

A hypothetical-operating rule for Lake Erie is included to simulate 3-lake regulation. The rule is an on-off (or deadband) rule curve that is added to or subtracted from the natural flow (Figure 4, from E. Megerian, U.S. Army Corps of Engineers, personal communication, 1993). Shown is the default curve, based on IJC Plan 50N, which can modify natural outflow by up to 50,000 cfs (1416 m^3/s) (IJC, 1989). STELLA allows the user to easily alter the regulation curve to simulate alternative capacities and trigger points. For example, the deadband could be shifted left or right to simulate different target means, and the maximum control capacity could be increased or decreased. Some of the participants took advantage of this capability to model the use of the existing Black Rock Lock in the Niagara River to control flows. Black Rock Lock's capacity would only be 15,000 cfs, but it would cost much less than Plan 50N (annualized cost: ~$3 M vs. ~$300M or more for 50N) (IJC, 1981, 1993), because only the existing lock channel would be modified.

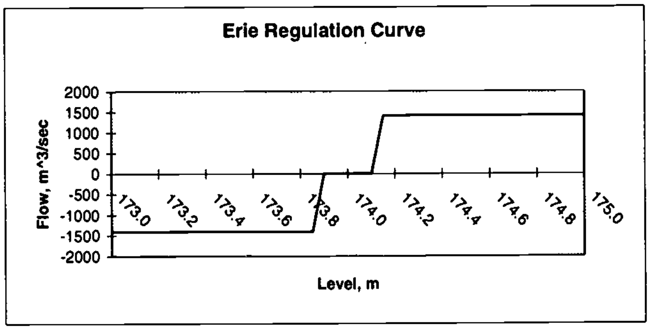


Figure 4. Niagara Flow Regulation Curve (Base 50N Plan).

Water temperature and percentage of ice cover are modeled because they are inputs to impact models. Water temperature is represented by linear regressions whose inputs are lagged water temperature, and present and lagged overland temperature. Also adopted are Croley's (1989a, 1989b) and Assel's (1983) model for ice cover as a function of monthly overland air temperature.

Impact Models

The impact models (Table 2) include just those impacts that are directly linked to the output from the hydraulic response model, namely water level or channel flow. While the economic impacts (hydropower, navigation and shoreline property damages) are widely recognized as major concerns, measures for ecosystem health are not generally agreed upon. Simple models of two important impacts were chosen: cold water habitat (CWH) and wetland vertical extent. Most of the impacts were disaggregated by lake because decisions about Superior and Ontario outflows and Erie control affect all lakes, even though the emphasis of the study is on Lake Erie water level regulation. The following paragraphs describe each of the impact models. Details are available in Chao *et al.* (1997).

TABLE 2. Impact Models and Their Sources.

Impact Model	Source
Socio-Economic	
Hydropower Value ($/yr)	IJC (1981, 1993)
Shoreline Damages ($/yr)	IJC (1993)
Navigation ($/yr)	Keith *et al.* (1989)
Recreation ($/yr)	User supplied
Investment Cost ($/yr)	User supplied
O&M Cost ($/yr)	User supplied
Environmental	
Cold Water Habitat (km^3)	El-Shaarwari (1984)
Wetland Area (m in vertical extent)	IJC (1993)

The hydropower models evaluate the monthly hydropower production for U.S. and Canadian plants along the St. Mary's, Niagara, and Upper St. Lawrence Rivers given channel flows as calculated by the hydraulic response model. The models calculate (1) flow allocations to each nation, (2) flow volume or head at each plant, (3) power according to efficiency curves, and (4) value of that power.

Riparian property damages are obtained using stage-damage curves showing expected inundation and erosion damages as a function of water level by month. The original curves (IJC 1993) exclude damages for January and February because shore ice encrustation prevents damages from occurring. As climate change may reduce the extent and duration of encrustation, the model includes hypothesized curves for January and February for a without ice condition. The damages from the curves are then scaled according to the amount of ice cover. Possible effects of shoreline management policies upon shoreline damage costs were analyzed by allowing the user to shift, scale and/or redraw the stage-damage curves using STELLA's graphic interface.

The navigation model calculates the monthly cost per ton averaged over all commodities and domestic routes as function of channel depths. It is a metamodel fit to the results of Keith *et al.* (1989). The latter model first calculates available channel depth given the route. Then given available water depth and ship class, the model calculates the maximum loading. The number of trips is calculated for total monthly tons of all the commodities, given the maximum loading for the fleet. Operating costs for each ship class and route times the number of trips is used derive the cost per ton.

Cold water habitat (CWH) is the mean volume of the oxygenated hypolimnion of the Lake Erie central basin in September. The Great Lakes Water Quality Agreement between the U.S. and Canada recognized that Lake Trout population, a cold water fish at the top of the aquatic food chain, would be a suitable indicator of ecosystem health for Lake Superior. CWH is a comparable indicator for Lake Erie because CWH determines the potential population capacity for cold water fish populations. After the spring turnover, the oxygenated portion of the hypolimnion slowly declines due to biochemical oxygen demand. September, the last month before the autumn lake turnover, is the critical month because it is when the oxygen in the hypolimnion is at its lowest. CWH is modeled by first calculating the volume of hypolimnion, given water levels and water temperatures (El-Shaawari, 1984). The probability that the hypolimnion is oxygenated is determined from a regression equation that is a function of September hypolimnion water temperature, phosphorus loading (assumed constant), and water level. The product of oxygenated proportion and total hypolimnion volume gives volume of CWH.

Wetland quality and extent is a function of many variables, with lake level fluctuations being among the most important. To simplify the modeling, the wetlands impact model simply measures the potential vertical extent of wetlands, i.e., the elevation difference between the lakeward and the landward boundary of the wetlands, as function of lake level variation. The IJC, lacking other comprehensive data particularly wetland surface area, developed this model to rely only on water levels as input (IJC, 1993). During a given year, the upper bound of potential wetlands (the elevation of the landward side) is the highest mean September water level that has occurred in the previous 18 years. Similarly, the lower bound of potential wetlands (the elevation of the lakeward side) is the lowest mean water level in May in the last three years. The model assumes the landward side must be flooded once in 18 years to ensure the seed bank is replenished with wetland plants. Similarly, seeds for emergent plants that have been underwater for more than three years are assumed to die.

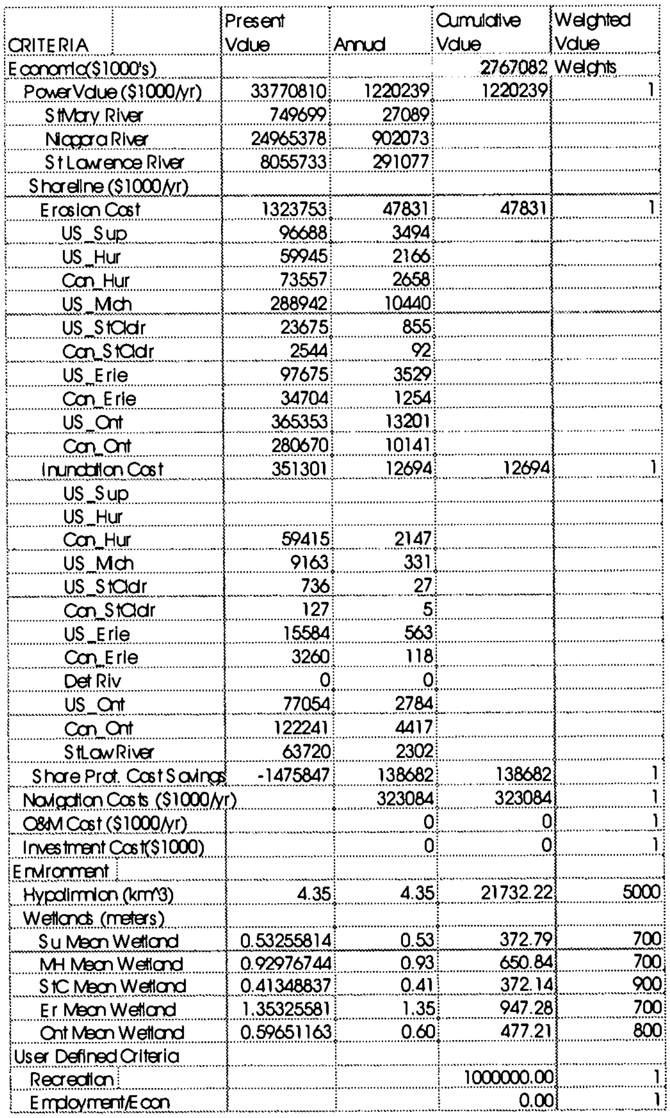
Decision Analysis Tools

The data from the hydraulic and impact models were automatically fed to the multi-criteria decision model, which was implemented in EXCEL® (Figure 5). The user simply entered tradeoff weights for the impact categories and an aggregate score was calculated from a linear additive utility function. There is a wide range of methods available to choose weights, which can differ significantly in their results (Hobbs *et al.*, 1992); here, tradeoff weighting was used because (in theory) it yields weights that reflect marginal rates of substitution, as they should. Since the emphasis of the workshop was upon creating a transparent tool for people to explore the performance of different systems, and not on the multicriteria tradeoff analysis, we decided to use the most simple, understandable approach. The users also specified a discount rate to calculate present worth. Scores for each scenario could be saved to compare later with other scenarios. The decision tree analysis also was calculated in Excel. The expected value of the alternatives under uncertainty was calculated according to the decision tree shown in Figure 2. Note that the tree assumes that the year 0 decision is irreversible. Thus this tree does not include the full range of options available especially the important option of delaying a decision until more information available. More sophisticated analyses can account for such options and possible reductions in uncertainties over time (Chao and Hobbs, 1997; Venkatesh and Hobbs, 1999). However, time constraints did not permit their consideration in these workshops.

WORKSHOP EXPERIMENTS

Pre- and post-workshop questionnaires for both workshops were used to elicit the participant's opinions of the value of the decision analysis tools for understanding the impacts of climate change and the evaluating the alternatives to ameliorate these impacts. The questions addressed these characteristics of the methods: ease of use, ability to focus on important issues, ability to provide consistency in decisions, ability to increase confidence in ranking of alternatives, and acceptability in a public planning setting.

In the first workshop, the participants learned how to use the DSS, participated in structured group discussions, and applied scenario analysis. The scenario analysis compared 2-lake regulation versus 3-lake regulation under the present climate and under a steady-state 2xCO_2 climate warming scenario based on results of the CCC-GCM. The group was divided into teams of two or three people for the scenario analysis. These sub-groups then specified their own assumptions concerning Lake Erie regulation rules, cost to implement 3-lake regulation, interest rate, and tradeoff weights.



CRITERIA	Present Value	Annual	Cumulative Value	Weighted Value
Economic($1000's)			2767082	Weights
Power Value ($1000/yr)	33770810	1220239	1220239	1
St Mary River	749699	27089		
Niagara River	24965378	902073		
St Lawrence River	8055733	291077		
Shoreline ($1000/yr)				
Erosion Cost	1323753	47831	47831	1
US_Sup	96688	3494		
US_Hur	59945	2166		
Can_Hur	73557	2658		
US_Mich	288942	10440		
US_StClair	23675	855		
Can_StClair	2544	92		
US_Erie	97675	3529		
Can_Erie	34704	1254		
US_Ont	365353	13201		
Can_Ont	280670	10141		
Inundation Cost	351301	12694	12694	1
US_Sup				
US_Hur				
Can_Hur	59415	2147		
US_Mich	9163	331		
US_StClair	736	27		
Can_StClair	127	5		
US_Erie	15584	563		
Can_Erie	3260	118		
Det Riv	0	0		
US_Ont	77054	2784		
Can_Ont	122241	4417		
StLawRiver	63720	2302		
Shore Prot. Cost Savings	-1475847	138682	138682	1
Navigation Costs ($1000/yr)		323084	323084	1
O&M Cost ($1000/yr)		0	0	1
Investment Cost($1000)		0	0	1
Environment				
Hypolimnion (km^3)	4.35	4.35	21732.22	5000
Wetlands (meters)				
Su Mean Wetland	0.53255814	0.53	372.79	700
MH Mean Wetland	0.92976744	0.93	650.84	700
StC Mean Wetland	0.41348837	0.41	372.14	900
Er Mean Wetland	1.35325581	1.35	947.28	700
Ont Mean Wetland	0.59651163	0.60	477.21	800
User Defined Criteria				
Recreation			1000000.00	1
Employment/Econ			0.00	1

Figure 5. Multi-Criteria Decision Model – Sample of Results.

The second workshop repeated the scenario analysis but with transient climate change scenarios instead of steady state scenarios. The transient scenarios included ones obtained from the MPI, UKMO, and GFDL GCMs, translated into NBS scenarios by the permutation procedure summarized above. In addition, users defined their own transient scenarios by specifying a change in precipitation and temperature for each lake 60 years hence, and then applying the permutation procedure. The second workshop concluded with decision trees analyses to see if the degree of belief (represented by subjective probabilities) in one scenario or another changes the decision. They constructed trees in which each climate chance node had four possible outcomes, $1xCO_2$, MPI, UKMO, and GFDL (Figure 2). Each subgroup simulated performance of the 2-lake and 3-lake alternatives under each of the scenarios. Each subgroup was asked in a questionnaire to specify subjective probabilities to each chance node of the tree. If the members of the subgroup disagreed on the subjective probabilities, they specified separate sets of probabilities. They then evaluated the expected performance of each alternative, and undertook sensitivity analyses of the probabilities.

In both workshops, structured group discussions, using the Nominal Group Method, were held on several issues concerning climate change, Great Lakes management, and the role of models were interspersed among the simulation exercises. Nominal Group discussions usually consist of silent writing of ideas, posting and round robin discussion of those ideas (subject to short time limits), voting, round robin discussion of voting results and, if desired, revoting (Delbecq *et al.*, 1975). The purpose of the Nominal Group technique is to facilitate efficient exchange of information and to prevent domination of discussion by aggressive group members.

RESULTS

This section is organized as follows. We first review the background of the participants and the results from the structured group discussions. We then discuss the results of the scenario analysis and decision tree exercises. Last, we summarize the participants' evaluation of the DSS and the decision analysis tools.

Great Lakes and Climate Change Planning

In the pre-workshop questionnaire and during the Nominal Group discussions, the participants stated their opinions on water planning and climate change. First, the questionnaire assessed the participants' opinions concerning 2-lake versus 3-lake regulation. All but one preferred 2-lake regulation to 3-lake regulation, consistent with the IJC's final recommendations. They also strongly favored non-structural shore protection alternatives, such as setbacks and elevation requirements, regardless of which lake level regulation plan was in place. Structural shore protection measures were viewed less favorably.

The questionnaires also showed that the participants were knowledgeable about the 1995 Intergovernmental Panel on Climate Change Study (IPCC, 1995). For instance, most knew the year 2050 was estimated as the year that a $2xCO_2$ scenario would be achieved. They recognized that changes in precipitation in the Great Lakes basin were highly uncertain; yet all believed Lake Erie water levels would decrease (giving an average estimate of 1.3 m with values ranging from 1 to 2 m) because of temperature increases, despite the possibility of precipitation increases.

Half of the participants' organizations had considered climate change in their water supply decisions through scenario analysis, although two participants noted that these analyses were done with scenarios of low flows that were not necessarily derived from climate change scenarios. One participant commented that "(c)limate change is being studied as to how it might influence design criteria and how to deal with it in planning." Three participants reported that climate change information had actually changed their organizations' decisions. In one case, consideration of climate 'led to the creation of the Great Lakes-St. Lawrence Basin Study supported by the Government of Canada's Green Plan.' In another, '(w)e looked at water supply in the Grand River (water conservation and quality), (and we) also are looking at (climate) adaptation alternatives.'

The first workshop began with a Nominal Group discussion to identify characteristics of water resources investments that are affected by climate change. The participants identified the following characteristics: long planning horizons, irreversibility (e.g., harbors and power plants), system complexity (recognition of which may lead to better understanding of system sensitivity to climate change), political factors (e.g., environmental regulations and the Niagara Treaty), and external factors (e.g., NAFTA, Mississippi River diversions, and sea level rise). The participants recognized that investment decisions could depend on which climate change scenario is believed. The participants defined two polar positions on climate change. A "non-skeptic" was defined as one who would consider possible climate change by focusing on system adaptation, system flexibility, contingency planning, and "no regrets" policies. A "skeptic" would demand the "weight of evidence" before they would respond to climate change.

The next Nominal Group topic concerned the information that would be needed to make decisions about water resources investments under climate change uncertainty. A useful DSS should provide some or all of this information. The participants identified the following information: better basin-scale climate models, a more comprehensive and uniform framework for benefit-cost and environmental effects analysis, and sensitivity analyses to identify sectors most susceptible/sensitive to climate change. The participants felt that water resource planning in the Great Lakes is more sensitive to uncertainty in economic growth and the type and effectiveness of future environmental regulations than to climate change. Other uncertainties that participants stated were as or more important than water level uncertainties included patterns of land use and invasions of exotic species. Nevertheless, most thought that climate change uncertainty still needs to be considered.

Scenario and Decision Tree Exercises

For the DSS exercises, the participants broke into subgroups of two or three persons each. For the first DSS exercise, each subgroup conducted a scenario analysis of 2- and 3-lake regulation alternatives. At the start of this exercise, the participants provided weights for the multi-criteria framework (Table 3), which were used to aggregate the multiple criteria into a single net benefits measure. In particular, weights were assessed by asking each person to state the amount of one criterion that they would be willing to give up to obtain a given improvement in another. In doing so, they largely treated the monetary measures as being equivalent ("a dollar is a dollar"), except where they thought the component models, which were based on data from the IJC Levels Reference Study, had a bias towards underestimating or overestimating effects. As an example of a perceived bias, the flood damages for the Canadian side of Lake St. Clair were calculated to be ten times that for the US side. The participants did not find this credible, so all the subgroups set the weight for Lake St. Clair flood damages to a low value. Meanwhile, the weights the subgroups assigned to wetlands varied greatly for two reasons: (1) wetland extent was expressed as range of wetland elevation without corresponding topographic relationships, so that wetland area could not be assessed, and (2) no information was presented to assess the dollar value of wetland area. Values ranged from zero to $8 million annually per foot of elevation, depending on the lake. The subgroups were also asked to assume a discount rate to calculate present worth; responses ranged from 3 percent to 10 percent/year. These responses reflected, in part, the participants' value judgments concerning the appropriate social rate of time preference.

The next step in the scenario exercise was for each subgroup to design the Lake Erie regulation rules under 3-lake regulation. The rules varied by the modified flow capacity (±12,000, ±25,000, or ±50,000 cfs were considered) and by the target elevation of the rule (173.5 to 174 m, where the long-term average level of Lake Erie is 174.1 m). Investment costs for Lake Erie control structures were assumed to be on the order of $300 million per year.

TABLE 3. Averages and Ranges of Criteria Weights.

Criteria	Mean (Range) of Weight
Hydropower ($/$)	1.0 (0.5 - 2)
Erosion Damages ($/$)	0.9 (0.3 - 1.2)
Flooding Damages ($/$)	1.1 (0.5 - 2)
Navigation ($/$)	0.8 (0.0 - 1.5)
O&M Costs of Regulation ($/$)	1.0 (0.5 - 2)
Annual Investment Cost of Regulation ($/$)	1.3 (0 - 5)
Cold Water Habitat ($1000/km^3)	$1113 (0 - 5000)
Superior Wetlands ($1000/ft)	$350 (0 - 2000)
Michigan/Huron Wetlands ($1000/ft)	$426 (0 - 3000)
St. Clair Wetlands ($1000/ft)	$828 (0 - 8000)
Erie Wetlands ($1000/ft)	$590 (0 - 5000)
Ontario Wetlands ($1000/ft)	$585 (0 - 5000)

The subgroups then used the DSS to evaluate the performance of the 2- and 3-lake alternatives under the 1xCO_2 and 2xCO_2 scenarios. The subgroups' conclusions varied because they made different assumptions concerning regulation rules, weights, and investment cost. Under the 1xCO_2 scenario, four of the five subgroups recorded negative net benefits for the 3-lake plan, ranging from -$92M/yr to -$30M/yr. The one group with positive benefits obtained +$19M/yr because they created an extra criterion for recreation, in which they assumed large positive benefits would accrue under 3-lake regulation. Thus, most groups concurred with the IJC study in that the investment cost of the regulation works was too high to be justifiable. The groups then repeated the simulation with the 2xCO_2 steady-state CCC-GCM scenario. Most found that 3-lake benefits improved under climate change because lake regulation minimized some of the negative impacts of lower water levels, particularly navigation and wetland impacts. Nonetheless, its net benefits were still negative for the same four groups that obtained negative benefits for the 1xCO_2 case.

The second workshop began with a second scenario analysis exercise, involving the three transient climate scenarios instead of steady state scenarios. Two subgroups still found that net benefits for 2-lake regulation was better than that for 3-lake regulation under all the scenarios, present and transient scenarios alike. The subgroup which authors added a criterion for recreation still found small positive benefits for 3-lake regulation under all the scenarios. The last subgroup found positive net benefits for the Black Rock Lock alternative under the present climate, but negative benefits under the MPI transient scenario. The MPI scenario, which yields the most severe decreases in NBS among the GCM scenarios, resulted in the lowest benefits, as hydropower and navigation suffered significantly. Each subgroup found that shoreline damages fell significantly under the transient climate change scenarios, consistent with Table 1. One group also reported that 3-lake regulation significantly reduced climate warming's impacts upon navigation because regulation would boost Lake Erie's levels in that scenario.

For the decision tree exercise, some subgroups found that their trees indicated that the decision to regulate Lake Erie would change as their belief in climate change changed, while 2-lake was always best for the other subgroups. One of these subgroups concluded that 3-lake regulation became attractive if $P(MPI) > 0.68$ and $P(1xCO_2) < 0.32$. Another subgroup preferred a half-sized 3-lake regulation (Plan 25N) to 2-lake regulation if $P(UKMO) > 0.3$ and $P(1xCO_2) < 0.7$. On the other hand, a third subgroup (whose decision tree is shown in Figure 2) preferred the smallest version of 3-lake regulation (Black Rock Lock) under the existing climate, so that if the probability of no climate change is sufficiently high, it would prefer to regulate Lake Erie. The remainder of the subgroups found that regardless of climate change, they would never choose Lake Erie regulation.

These results illustrate how beliefs about the likelihood and magnitude of climate change can affect water investment decisions being made today, confirming analytical results (Chao and Hobbs, 1997; Hobbs *et al.* 1997). They also show how user judgments can drastically affect the results, reinforcing the need for a DSS that facilitates changing and exploration of assumptions.

Evaluation of Methods (Discussion and Questionnaires)

Post-workshop questionnaires revealed that, overall, the participants felt that the DSS exercises did not change their opinions about 3-lake regulation under climate change uncertainty – 3-lake regulation still was not preferred over 2-lake regulation – despite the results of the decision tree exercise. Several did observe that climate change might increase the attractiveness of modified 2-lake schemes compared to the present 2-lake regulation scheme. The DSS also generated practical insights about the Great Lakes system. For instance, some participants concluded that the Black Rock Lock alternative might be an attractive 3-lake option because of its low cost.

The questionnaire also addressed the utility of the decision analysis methods. The participants found the methods easy to comprehend. But they felt that more sophisticated approaches may not be applicable in the real world, in particular assigning tradeoff-based weights for multi-criteria decision making and deriving subjective probabilities for decision trees. Table 4, for example, shows how the participants voted on the ability of the methods to improve consistency of decisions. The answers were broadly similar for questions concerning the ability of the methods to help users focus on important issues and to increase confidence in rankings of alternatives. In general, simulation modeling, scenario analysis and structured group discussion were viewed favorably, while decision trees were viewed as less effective.

TABLE 4. Participant Response to the Statement, "Do you think the methods would help improve the consistency of decisions compared to present analysis and planning methods?"

Method/	Disagree			(percent)			Agree
Concept	-3	-2	-1	0	1	2	3
Simulation Modeling					10	40	50
Scenario Analysis			14	14	14	14	42
Decision Trees			14	14	72		
Nominal Group				22	22	34	22

The participants found that the graphical interface of the simulation model made the system readily understandable. They liked being able to conveniently change the operating rules, and to quickly see the results. The participants cautioned that the simulation model would only be as good as the data that goes into it. One comment was "I think modeling of complex systems is a wonderful tool, sharpening the analysis, noting sensitive variables, and forcing one to quantify things." Another comment was that the simulation model was good for encouraging diverse users to discuss inputs, making them more meaningful and consistent; however, the final outcomes of the decision process may not be any better because of political considerations. Nevertheless, most felt that the DSS made scenario analysis practical for planning studies.

The Nominal Group Discussion was generally highly regarded for generating thought-provoking ideas and exchanging opinions. However, the participants had stronger reservations about decision trees. Although decision trees were easy to understand, "applying and believing in their results [would be] more difficult." In particular, eliciting levels of belief (probabilities) in climate change scenarios was perceived as unreliable. Assuming a public planning study is carried out over several meetings and that attendance at such meeting may be intermittent, the level of involvement required to understand and appreciate such methods may not be possible. Nevertheless, all respondents recommended that decision trees and value of information analysis be used in planning, if not necessarily by members of the public themselves.

CONCLUSION

This study sought to examine how climate change and its impacts can be incorporated into management of the effects of varying Lake Erie levels. Several decision analysis methods were evaluated, including simulation modeling, scenario analysis, decision trees, and structured group discussions. To evaluate the decision analysis methods, we interviewed the participants before and after the workshops. The first three methods build upon each other. Simulation modeling enables the user to understand the complex links between climate and water resources. Scenario analysis tests the robustness of management alternatives. If one management alternative is preferred under all scenarios, then one may conclude that climate change does not affect the decision. If different alternatives perform better under different scenarios, then decision trees can be used to consider the likelihood of each scenario occurring and to choose the alternative that maximizes the (probability weighted) expected net benefits. Structured group discussions supplement the other methods by facilitating generation of ideas and improving understanding of the other parties' positions.

We conclude that in large planning exercises, where the background of participants will vary greatly, use of a DSS together with structured group discussions can improve the consistency of inputs to a decision and facilitate agreement. Other evidence of this includes a drought management study in which the Corps of Engineers provided individual copies of a STELLA-based DSS to stakeholders (W. J. Werick, W. Whipple, Jr., and J. Lund, 1996, Basinwide Management of Water in the Alabama-Coosa-Tallapoosa and Apalachicola-Chattahoochee-Flint River Basins, draft report, U.S. Army Corps of Engineers). The stakeholders were able to play with the model on their own, and the impacts of management alternatives were better agreed upon as a result.

The user-friendliness of the DSS also makes scenario analysis practical for large public planning studies, such as the IJC's Levels Reference Study. Scenario analysis is possible not only for climate change, but also for other system uncertainties. The decision tree analyses indicated that belief in the likelihood of climate change might change the management decision. On the other hand, the participants' sometimes skeptical reaction to subjective probabilities leads us to conclude that there are obstacles to gaining acceptance for decision trees in planning studies that involve the public. Assigning subjective probabilities may not be understood and therefore the results from a decision tree may not be trusted. However, decision trees would still be useful for analysts and managers who wish to quantify the value of information and of flexible strategies that keep options open (Hobbs *et al.*, 1997); scenario analysis cannot be used for that purpose. Decision trees can also be used in a sensitivity analysis mode to explore how different beliefs concerning climate change might affect the relative attractiveness of the alternatives. Last, the participants liked structured group discussions for their ability to elicit diverse opinions. They felt structured group discussion would be particularly suited for public planning settings where different interest groups may not have a good understanding of each other's positions and where often times dominant personalities prevent open discussion.

On a practical note, the workshops did not greatly change opinions of the participants regarding water level management in the Great Lakes. In particular, the participants still generally preferred modified 2-lake regulation regardless of climate change, although some participants were surprised to find that 3-lake regulation was found advantageous under some scenarios, especially when down-sized (Black Rock Lock, which is 70 percent smaller than the full Plan 50N). Nonetheless, the participants felt strongly that climate change should be included in future studies of Great Lakes water level management. More specifically, the participants recommended that additional research be conducted on better GCMs, more comprehensive evaluation frameworks, and identification of the most susceptible economic sectors. The Institute for Water Resources of the U.S. Army Corps of Engineers is presently using the DSS for climate change impact studies and evaluation of Lake Ontario regulation rules.

ACKNOWLEDGMENTS

The authors would like to thank all the dedicated Great Lakes water resource planners, policy makers, and researchers who participated. We would also like to acknowledge the assistance of the following students who helped to prepare the material for the workshop and to run the workshop: J. Bloczynski, B. Schmotzer, and S. Brandt. This work was supported by the National Science Foundation under Grant SBR92-23780, USEPA under Grant R825150010, and the Institute for Water Resources of the US Army Corps of Engineers. We thank E. Z. Stakhiv of IWR for encouraging this research. The workshops were held while the authors were with the Department of Systems Engineering, Case Western Reserve University, Cleveland, Ohio. The participants dedicated the workshops to their late colleague Benjamin DeCooke, whose contributions to our knowledge of Great Lakes hydrology and hydraulics is invaluable.

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